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The development of light, compact incineration technology is one alternative for dealing with shipboard waste disposal when overboard disposal is prohibited. The present research supports the development of an acoustically enhanced afterburner system that is targeted to these requirements. The afterburner is optimized when both CO and residual organic emissions are below acceptable thresholds. Our work showed that different pollutant emissions arise in different physical locations in the afterburner. Thus, minimization of one pollutant (*e.g.*, CO) can lead to an increase in another (*e.g.*, organics), and optimization involves the selection of operating conditions that recognize the trade-off between the various pollutants.

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Final Technical Report for: Performance Analysis of Shipboard Waste Incinerators for On-Line Control
(ONR N00014-97-1-0884)

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FAILURE MODE ANALYSIS OF THE ADVANCED, ACOUSTICALLY-FORCED AFTERBURNER FOR SHIPBOARD WASTE INCINERATION

Abstract

In response to international protocols and domestic initiatives the Navy needs to develop means of dealing with shipboard-generated wastes during those times when overboard disposal is prohibited. One approach is a novel shipboard incineration technology. This makes use of a pyrolyzer that takes the myriad of wastes generated at sea and transforms them into a generic, high heating value gaseous fuel stream. The use of existing land-based technology to burn this stream is unacceptable due to the size and weight of commercial afterburners. The alternative investigated in this initiative is an actively controlled, acoustically-forced afterburner. Our base grant focused on identifying the chemical and physical processes that control the performance of the afterburner, and on characterizing chemical surrogates whose appearance in the exhaust can be used as indicators of the approach of non-optimal operation. The goal is to use this real-time surrogate information as part of a control strategy. The work under the AASERT grant that is reported here involved the chemical kinetic modeling and data interpretation associated with this overall goal. Our work showed that different pollutant emissions arise in different physical locations in the afterburner. Thus, minimization of one pollutant (*e.g.*, CO) can lead to an increase in another (*e.g.*, organics), and optimization involves the selection of operating conditions that recognize the trade-off between the various pollutants. Based on this work, we suggested a means of simultaneously improving the performance for both CO and organics. We also identified four specific failure scenarios for the afterburner, and experimentally investigated two of these. The results indicated that both lean extinction and fuel-rich operation could be detected by the appearance of formaldehyde. The rich case could be distinguished from the lean case by the appearance of high CO concentrations along with the formaldehyde.

Introduction

The U.S. Navy is developing novel incineration technologies to achieve high waste destruction efficiencies in small-sized units for shipboard applications. A consortium of Navy laboratories, universities, and research firms has been developing one approach. This consists of a small pyrolyzer system that reforms solid and liquid waste into a high-quality gaseous fuel stream. This stream is burned in an advanced, actively-controlled afterburner whose design is based on acoustically-forced periodic vortices. These coherent eddies dramatically increase the mixing rate of fuel and oxidizer (normally the rate-limiting factor in afterburners), which increases the overall waste destruction efficiency of the unit and significantly reduces the size needed to achieve acceptable performance.

Figure 1 shows a schematic of the unit. The modulated air stream produces regular, periodic annular vortices at the dump plane of the combustor. The pyrolysis product gas ("fuel") is added at the lip of the dump plane. The two streams are mixed before combustion starts (shown as the green eddy), and become ignited after the eddy has detached (shown as the red eddies). Note that

the exact arrangement of the fuel jets and secondary air jets (not shown) is a critical design feature and has been the subject of considerable work.

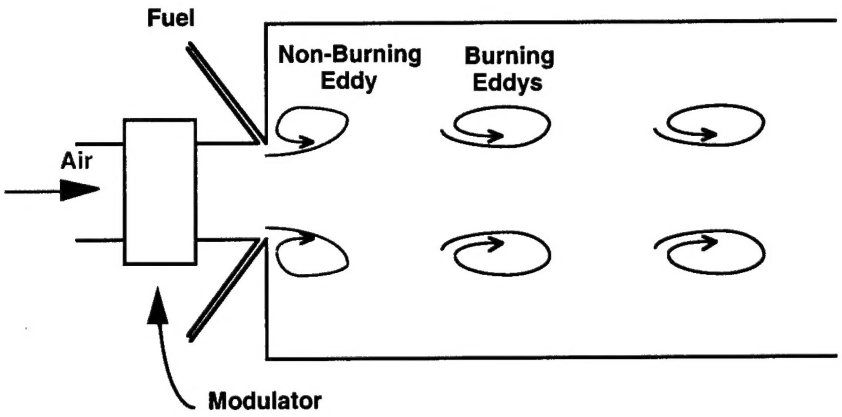

Figure 1. Schematic of the acoustically-enhanced, actively-controlled afterburner.

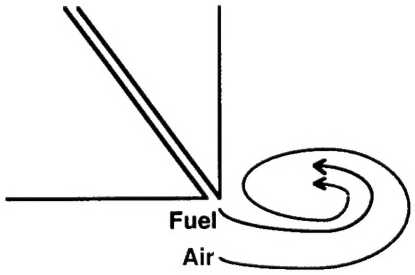

Figure 2. Detail of mixing processes occurring near the dump plane lip.

Figure 2 shows the manner in which the fuel gas mixes into the eddy. The intense strain occurring within the eddy leads to the formation of a nearly premixed packet of fuel/oxidizer before ignition takes place. Upon igniting, the packet burns as a premixed packet rather than as a diffusion flame. This simultaneously

1. Increases the burning rate. Since random turbulent mixing is normally the rate limiting step in turbulent diffusion combustion, acoustically-forced mixing allows combustion to be completed in substantially shorter times and distances.
2. Avoids the formation of rogue pockets of undermixed fuel by forcing premixing before the fuel is ignited. The presence of a small fraction of unmixed fuel in turbulent diffusion flames is thought to be the principal source of unburned organic emissions in gaseous incinerators.
3. Minimizes NO_x emissions by avoiding high temperatures. In normal incinerators the stoichiometric interface is a region of high temperature where the vast majority of NO_x formation occurs. The present system lacks such a stoichiometric interface.
4. Prevents soot formation. The present system lacks the high-temperature fuel rich pockets that are needed to generate soot.

A principal goal is to completely destroy the trace organics contained in the fuel gas. The principal operational challenge to this is the potential for unevenness in the feed. Too little waste can lead to a flameout condition, while too much can temporarily overwhelm the air supply, leading to high CO and organic emissions.

Subscale testing of the concept shows extremely good performance. However, two of the implementation challenges facing the concept are scale-up and control. Other members of the consortium have successfully addressed the scale-up issue. The control issue involves (1) understanding the mechanisms that govern the performance of the unit, and (2) using this information to develop algorithms to detect departures from optimal operation and to guide the return to the set point. A key issue is handling the uneven feed problem noted above.

One of the problems this approach shares with all other incineration technology is the lack of a direct means of continuously monitoring performance. In other words, means do not exist to continuously measure organic effluent concentrations to determine when the incinerator falls out of optimum performance. One approach is to use surrogates whose concentrations *can* be continuously measured and who can act as indirect indicators of performance. The critical requirement is that the exhaust concentrations of the surrogates and the target wastes be correlated in a known way during each of the possible incinerator upset modes. One goal of this project is to define the effectiveness of potential surrogates as indicators of performance upset. A second goal is to evaluate whether these surrogates can be used (1) as a "fingerprint" that indicates how the unit has moved out of compliance, and (2) as a means of directing the on-line control system back to optimal operation.

Afterburner Performance Analysis

Those involved in the science of thermal waste destruction have long recognized that the mean times and temperatures provided by industrial incinerators are considerably more than sufficient to effect complete destruction of organic wastes. The fact that all incinerators emit some small fraction of their input waste is universally attributed to the existence of mass transport constraints in the turbulent flames. Within the turbulent flame, a small fraction of the waste experiences an environment that is unfavorable for complete waste destruction (*e.g.*, too cold or too fuel-rich). These pathways represent the mechanisms that limit the performance of correctly operating incinerators. Identifying and closing these pathways are important steps in improving the baseline performance an existing incinerator design.

These pathways have traditionally been termed "failure modes." This does not, of course, indicate an operational failure on the part of the incinerator, but instead refers to the specific performance-limiting pathways by which waste exits the unit. As such, failure modes are often contained in the tails of the mixing, temperature, and residence time distribution functions, and are thus difficult to analyze based on mean flow models. The following provides a brief summary of the results of our analysis of the 50 kW actively controlled afterburner. A principal tool used in the analysis is the large eddy simulation (LES) modeling results of Menon from Georgia Tech (a member of the consortium).

A number of pieces of operational data from the afterburner provide critical information on failure modes, as illustrated by the data of Figure 3. These include:

- The overall stoichiometry of the afterburner must be quite fuel-lean to avoid emission of CO. A Φ_{FA} of less than 0.6 is required. This indicates the presence of some unmixedness, and that the last major fuel-rich pocket is turned lean only by driving the entire afterburner to a relatively low value of Φ_{FA}.
- Operating with Φ_{FA} >0.6 results in CO emissions, but also results in high DRE. This is relatively easy to rationalize since hot, moderately rich pockets are capable of essentially complete conversion of waste to CO, even if insufficient O_2 is present to oxidize the CO.
- DRE continues to develop with downstream distance in the afterburner up to an axial distance of 0.4 m from the injection plane. The rate of development is, however, well below the rate predicted by pure kinetics. This suggests the importance of transport processes to performance, as discussed above.

- The ignition standoff is approximately 4 cm downstream of the inlet plane. This allows significant mixing to occur before the chemistry is initiated.

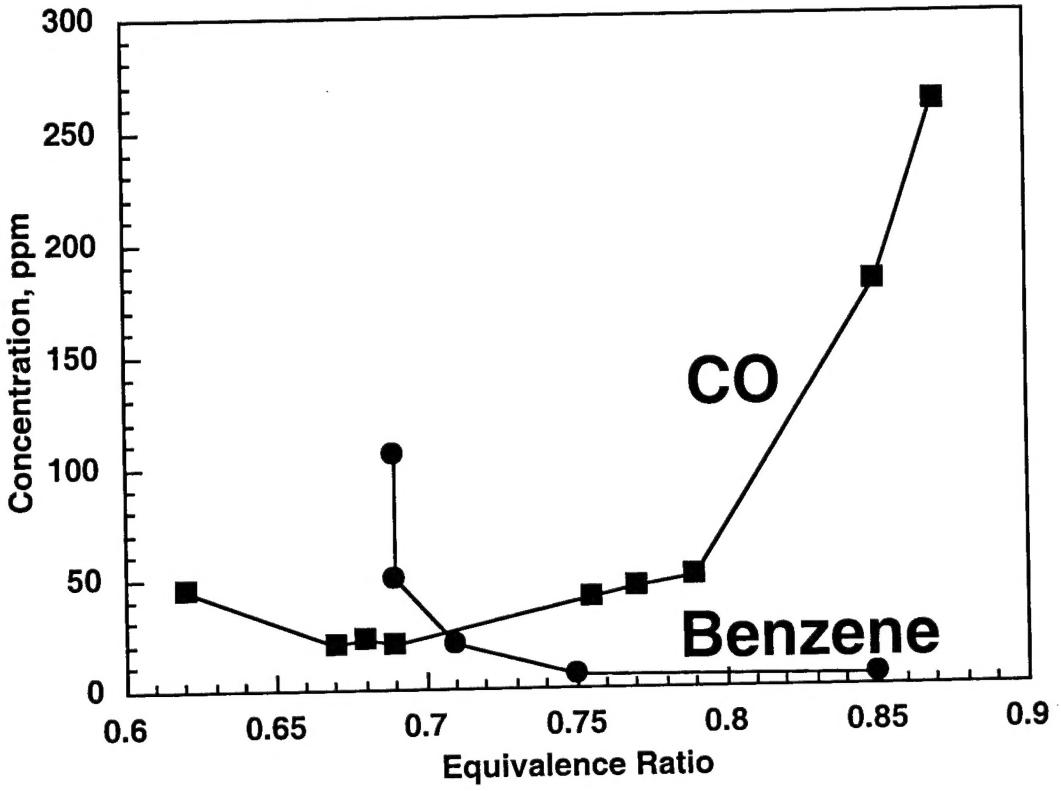

Figure 3. Data for the 50 kW afterburner showing the variation of CO and benzene emissions as a function of stoichiometry.

The LES results of Menon provide a time-unsteady picture of the evolution of the flow field and mixture fraction field from cycle to cycle over the acoustic forcing period. This allows one to locate regions of high stoichiometry and cold temperature within the current system.

The eddies are not perfectly mixed. Instead, they have structure with the center more fuel rich than the edges. Figure 4 shows a spatial profile of stoichiometry (plotted as Φ_{FA}) across an eddy as a function of time of. The figure shows that the core can actually be fuel-rich at early times. Due to the delay in the ignition of the eddy, the core burns initially in a rich, premixed mode rather than in a diffusion mode.

From analysis of the data, the eddy lifetime appears to be divided into four regimes. These are:

1. Entrainment of air into the eddy before ignition ($0 \le t < 5$ ms). This results in a partially premixed fuel packet.
2. Entrainment of air into the fuel eddy after ignition ($5 \le t \le 12$ ms). This is evidenced by the growth of the eddy and the decrease of the average rotating velocity.
3. Minimal entrainment, but continued mixing within the eddy ($12 \le t < 40$ ms). In this region, the eddy does not change in size or velocity appreciably, but the gradients within the eddy relax due to internal mixing.

4. Minimal mixing (t≥40 ms; x≥40 cm). After this point, little mixing or reaction occur. This corresponds to the point beyond which DRE ceases to improve in the data.

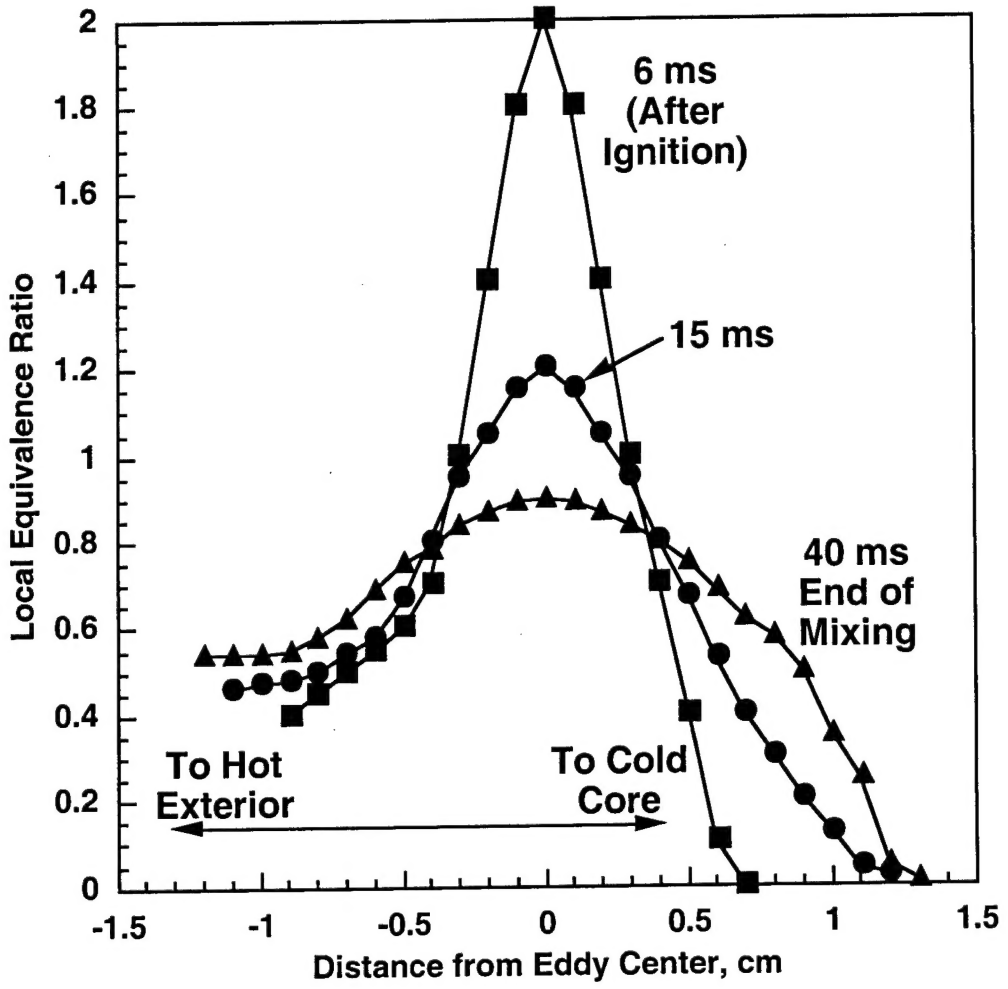

Figure 4. Evolution of stoichiometry profile across a single eddy as a function of its time of flight, as extracted from the LES data of Menon (■-6ms, ●-15ms, ▲-40ms).

CO escapes because the center point of the eddies remain fuel rich at the point where mixing ceases in Regime 4. For the case shown in Figure 4, sufficient overall air is supplied such that the center of the eddy has become fuel-lean by the point where mixing stops. As noted in the 50 kW data, this entails selecting an overall Φ_{FA} that is quite lean. It is important to note that although the center of these eddies may remain fuel rich, the high temperature ensures that organics are locally completely destroyed.

Organic emissions result from an interesting competition between mixing and reaction. The edge of the eddy in contact with the central core of cold air contains organics under conditions that are too cold to react. The internal mixing associated with Regime 3 brings these organics into contact with the hot core, leading to reaction. At the beginning of Regime 4, the mixing, and therefore reaction, ceases. Any remaining organics near the margin of the eddy become "frozen" and will fail to react.

The process is probably best illustrated by following the evolution of a Pdf of the stoichiometry (mixture fraction), as shown in Figure 5. At the ignition point, the mixture fraction lies on both the lean and rich side of stoichiometric. As the ignited eddy entrains air, the entire Pdf moves to left. In Regime 3 the mean of the Pdf remains stationary, while the wings move closer due to internal mixing. After the start of Regime 4, any portion of the Pdf remaining to the right of Φ_{FA} =1 will generate CO emissions. Any portion to the left a critical line (i.*e.*, too lean) will not experience complete benzene destruction, which will result in a finite benzene emission.

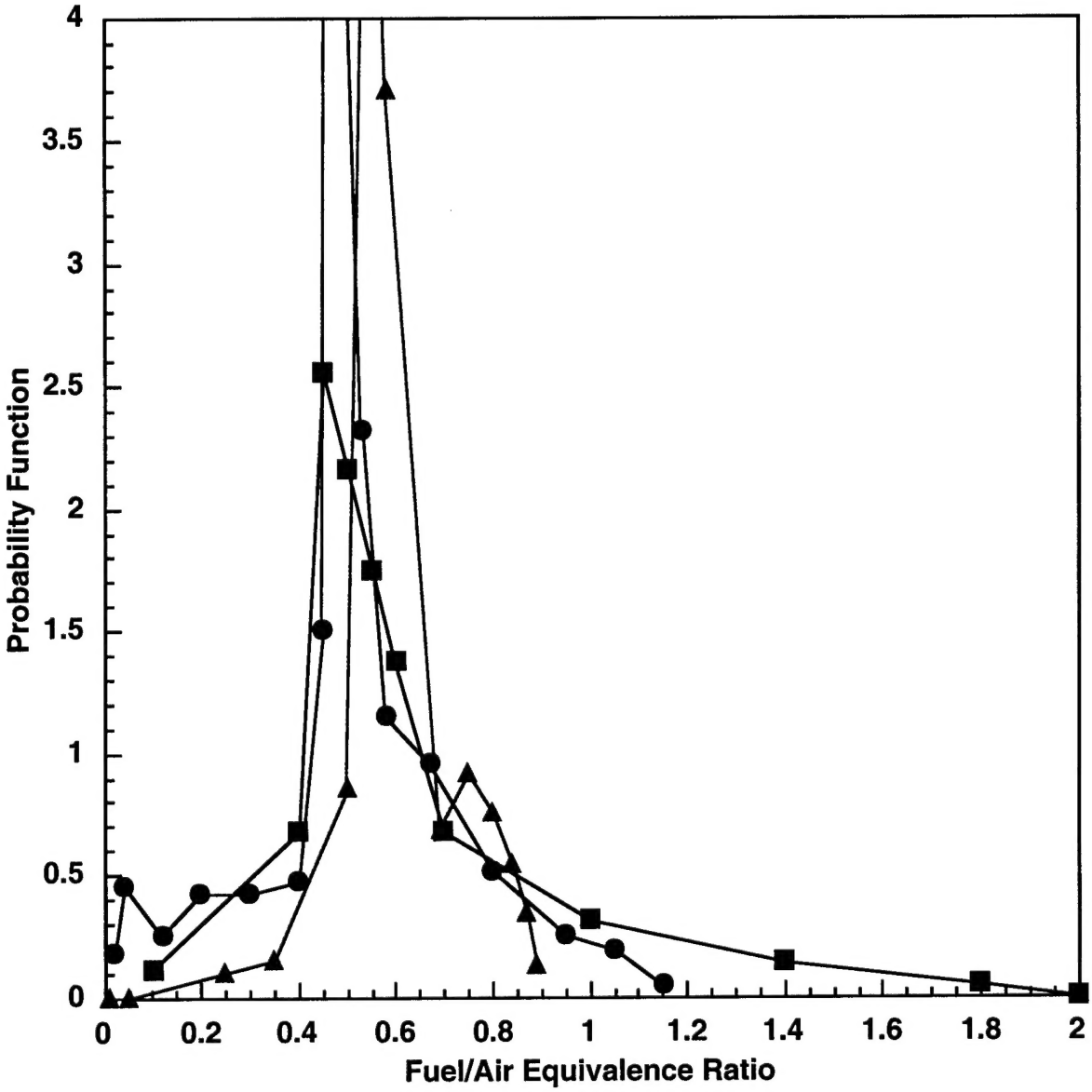

Figure 5. Evolution of the stoichiometry PDF across a single eddy as a function of its time of flight, as extracted from the LES data of Menon (■-6ms, ●-15ms, ▲-40ms).

Thus, the system must be operated at sufficiently lean conditions to ensure that all the rich zones (and CO) are scrubbed out of the center of the eddies. This, however, tends to reduced the temperature at the edge of the eddies, with harms DRE. This leads to the problem shown in Figure 3: The DRE and CO optimize at different values of Φ_{FA}. One approach to improving performance is to inject some air with the fuel, while at the same time moving the overall afterburner

stoichiometry closer to unity. The additional air will ease the erasing of the rich zone in the center of the eddy, while the increase in stoichiometry will lead to hotter eddies and better DRE.

Surrogate Identification

As mentioned above, organics generally escape from turbulent diffusion flames due to the presence of pathways that are either too cold or too fuel-rich to allow complete organic destruction. These pathways are normally associated with the tails of the temperature and stoichiometry distribution functions, and as such only a small fraction of the incinerator effluent is exposed to these environments. The first step in establishing suitable surrogates is to identify the specific environments (*i.e.*, pathways) that lead to waste emission in the present unit. The next step is to simulate these pathways such that the response of the waste organics and potential surrogates can be observed and correlated.

Review of afterburner operation has led to the development of four hypothetical "failure modes." These are:

- The approach of a premixed eddy to the lean flammability limit. This could occur due to a momentary reduction in the heating value or flow of the fuel gas, leading to low-temperatures in the eddies, or erratic flame stabilization. This problem is of considerable practical importance since the feed rate to the pyrolyzer and composition of the waste are difficulty to control.
- The approach of a premixed eddy to the rich flammability limit. This occurs due to an oversupply of fuel to the pyrolyzer, or due to the generation of a fuel gas with a high oxygen demand.
- A mistune of the flow field (*e.g.*, mistune of the acoustics), leading to poor mixing and the development of diffusion flame structures. Diffusion flames lead to high local temperatures (*i.e.*, high NOx), soot, and CO that must be mixed and oxidized.
- Introduction of a very flammable gas from the pyrolysis unit (*e.g.*, high H_2 concentrations), that allow the flame to attach to the burner lip. This causes the eddy to burn as it mixes, leading to a diffusion flame environment with all of the problems noted above.

The approach adopted is to simulate the time unsteady evolving eddy as a stationary, steady-state eddy using a stirred reactor. The stationary eddy is scaled such that the Damköhler number is the same between the actively-controlled afterburner and the stirred reactor experiments. Since the characteristic chemistry time scale is essentially the same between the two experiments, this implies that it is the characteristic time for mixing that must be matched.

The stirred reactor used to simulate the eddy is shown in cross-section in Figure 6. It consists of a cavity of 15.8 cm^3 volume that is fired by a single jet on the lower boundary. The jet strikes the opposite blank wall and establishes a torrodial recirculation pattern. Six exhaust ports are spaced around the lower end of the reactor near the feed jet.

To simulate the pyrolysis gas, the reactor is fired on a premixed CO/H_2 fuel containing 1250 ppm toluene to represent the trace organics. The product gases are analyzed by a combination of flame ionization gas chromatography and Fourier Transform Infrared Spectroscopy. Under the present grant, the first two failure modes were investigated (*i.e.*, fuel-lean premixed failure and fuel-rich premixed failure).

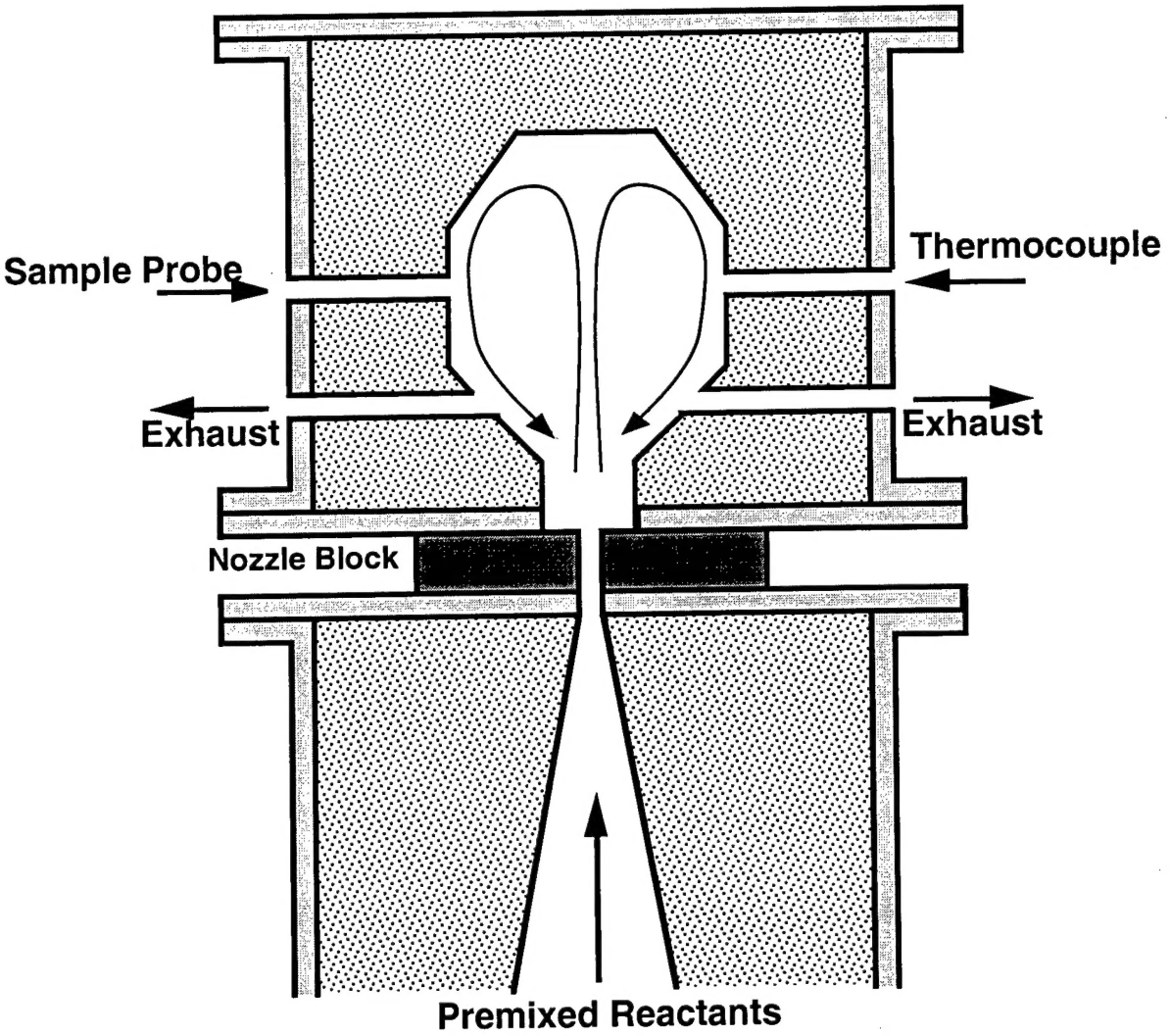

Figure 6. Schematic of the stirred reactor.

Results for the equimolar CO/H_2 mix are shown in Figure 7. Formaldehyde is an important byproduct as the extinction point is approached. Also, significant toluene appears near the extinction point. Finally, benzene appears here as a trace species. Other tests not shown (with propane as the fuel) showed much higher formaldehyde concentrations near extinction, much lower toluene emissions, and a total lack of benzene.

Chemical kinetic modeling of this system using detailed chemistry and a perfectly stirred reactor code showed that the formaldehyde and toluene concentrations are much higher in the data than would be predicted by the model. This is attributed to the breakdown of reactor homogeneity as extinction is approached. A Pdf mixing model utilizing a Monte Carlo solution procedure was developed to capture non-homogeneous behavior near the extinction point. This model was formulated by allowing packets of cold, unreacted gas to enter the reactor and mix at a rate set by Curl's model with the packets already in the reactor. Figure 8 shows a scatter plot of temperature vs. benzene concentration. The unreacted parcels (below ~1250 K) show the simple effects of dilution (*i.e.*, mixing with warm, benzene-free gas leads to packets in which the temperature is increased by the proportion to which benzene is diluted). At high temperatures, benzene is completely consumed, leaving a concentration of zero. At intermediate temperatures, partially-reacted packets exist. When the model is pushed to extinction, some of the partially reacted

packets are quenched by other cold packets. These quench events yields formaldehyde. This behavior would not be captured by a simple homogeneous model, and we believe it qualitatively represents the source of the formaldehyde seen in the data.

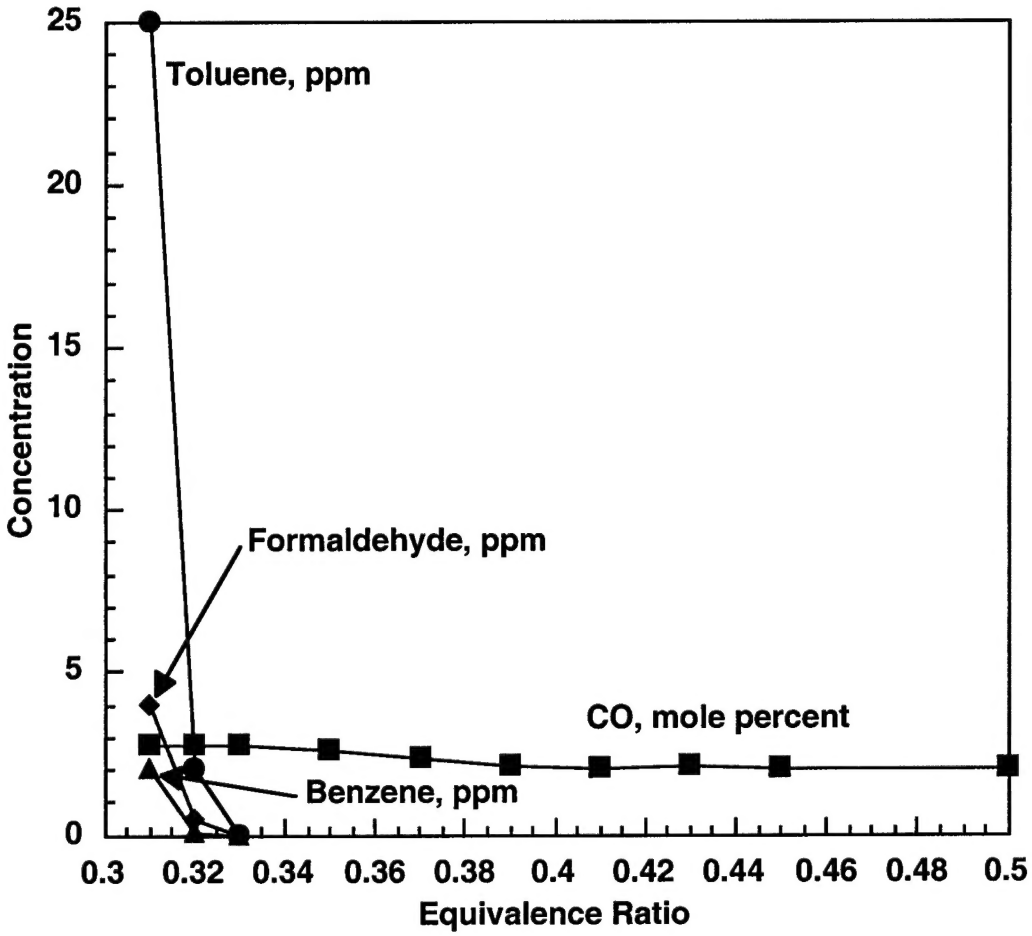

Figure 7. Trace species measurements on approach to extinction for a propane flame containing 1250 ppm toluene.

The next situation modeled was that of the fuel-rich premixed eddy. Under this condition, the eddy in the afterburner remains strongly mixed, but an oversupply of fuel depletes the local O_2. These tests are performed by holding the air flow constant and increasing the fuel flow. Dilution nitrogen is included as a feed for a number of these tests to directly determine the influence of temperature on the product species.

The results show, not unexpectedly, that toluene and benzene concentrations are quite low. Hot, fuel-rich conditions are, of course, quite favorable for the destruction of organic species. The CO concentrations are quite high, and are approximately correlated by a simple stoichiometric calculation. Surprisingly, formaldehyde appears as a significant emission. Its appearance is favored by lower temperatures and richer stoichiometries. The experiments show that temperature is the key variable, and that a very wide range in fuel-rich stoichiometries leads to a much smaller variation in formaldehyde emissions.

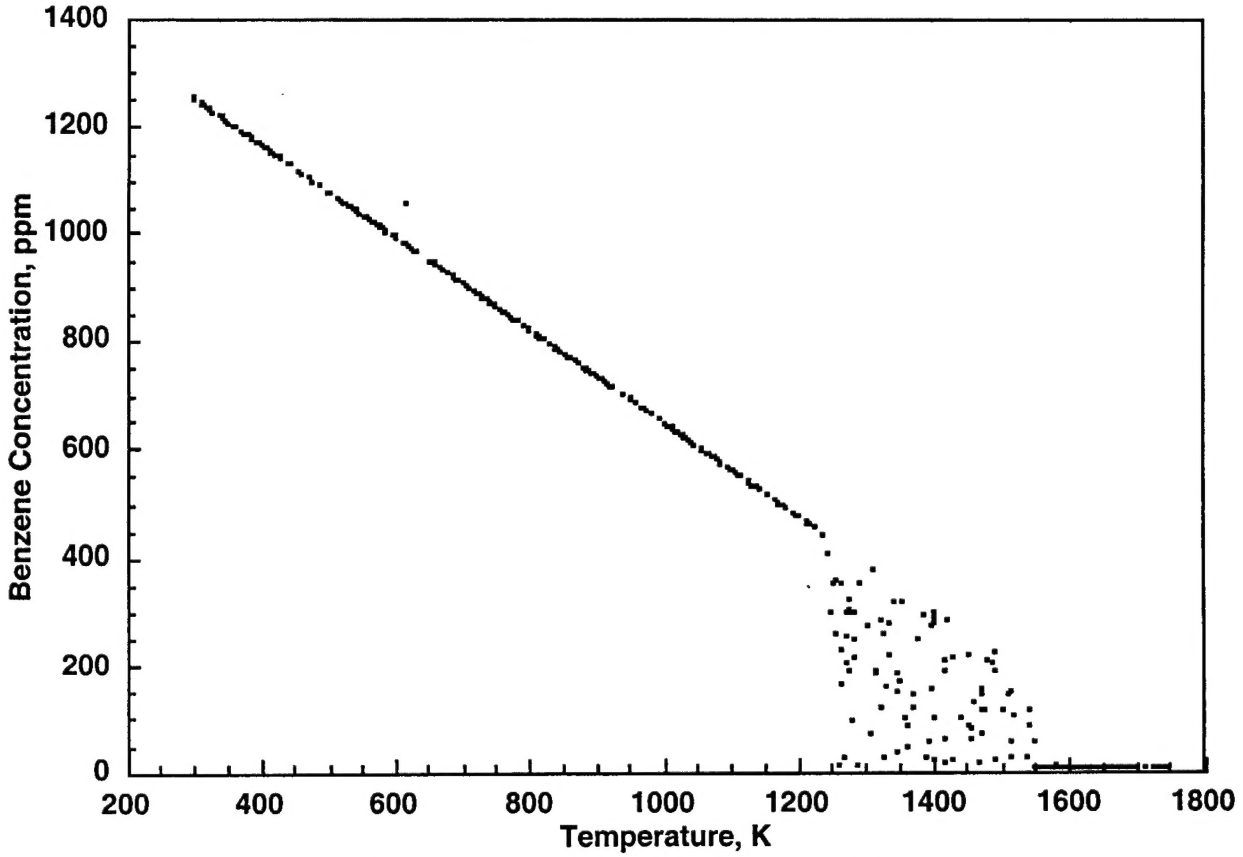

Figure 8. Results of the PDF calculation showing regions of no reaction, partial reaction, and complete reaction.

Conclusions

The acoustically driven afterburner represents a way to enhance waste destruction performance while significantly reducing the physical size of the unit. One of the major implementation problems is feedback control to ensure optimum performance at all times for an unattended unit. In the present work we developed an experimental model of the eddies generated by the acoustics in the afterburner. These eddies were then forced into non-optimum operating conditions to identify which species could be used as indicators of the onset of failure. To date we have investigated two candidate "failure modes." When the eddy approaches lean extinction, toluene (as the original feed organic) breaks through just prior to the flameout point. Both benzene and formaldehyde also appear at blowout, but in much lower concentrations. Under fuel rich conditions, very little of the original organics are observed, but formaldehyde becomes a significant emission. Since the premixed lean- and rich failure conditions are expected to be the most common in practice (since waste feed rate and quality are expected to be difficult to control), the differentiation of these two failure conditions is critical for failure detection and process control. The results suggest that formaldehyde can be used to detect either failure condition, and that the appearance of percent quantities of CO can be used to differentiate between the two.

An analysis of LES results on the original acoustic afterburner design showed that under optimum conditions, the waste and CO emissions originate at different points in the flow field. This explains why waste and CO emissions are minimized at different overall afterburner stoichiometries. It also suggests simple approaches to improve overall afterburner performance. Here, some air can be introduced with the fuel, while simultaneously the overall stoichiometry is move towards unity. This will ensure (1) that rich conditions at the center of the eddies are avoided, and (2) that the system is not too lean to effect complete waste destruction.